Energy Policy 41 (2012) 340–347

Contents lists available at SciVerse ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Nonrenewable energy cost of corn-ethanol in China

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ARTICLE INFO

Article history:
Received 24 July 2010
Accepted 28 October 2011
Available online 17 November 2011

Keywords:
Nonrenewable energy cost
Biofuel
Corn ethanol

ABSTRACT

Nonrenewable energy cost is accounted for the believed renewable biofuel of corn-ethanol in China. By a process-based energy analysis, nonrenewable energy cost in the corn-ethanol production process incorporating agricultural crop production, industrial conversion and wastewater treatment is conservatively estimated as 1.70 times that of the ethanol energy produced, corresponding to a negative energy return in contrast to the positive ones previously reported. Nonrenewable energy cost associated with wastewater treatment usually ignored in previous researches is shown important in the energy balance. Denoting the heavy nonrenewability of the produced corn-ethanol, the calculated nonrenewable energy cost would rise to 3.64 folds when part of the nonrenewable energy cost associated with water consumption, transportation and environmental remediation is included. Due to the coal dominated nonrenewable energy structure in China, corn-ethanol processes in China are mostly a conversion of coal to ethanol. Validations and discussions are also presented to reveal policy implications against corn based ethanol as an alternative energy in long term energy security planning.

1. Introduction

Interest in bio-ethanol as a substitute energy supply for nonrenewable fossil fuels has been growing since 1990s in China. Launched by the government in December 2002, pilot works have been carried out in two provinces to test the use of E10 (a kind of bio-ethanol blend with 10% ethanol and 90% gasoline in volume) as automobile fuel (YCADI, 2003), and later extended to nine provinces in 2005 (YCADI, 2005). According to the Tenth Five-Year Planning (2001–2005) on bio-ethanol fuel, China has authorized four pilot projects on bio-ethanol, with total capacity of 1.02 million tons per year, of which 0.80 million tons are made from corn, using about 2% of the total corn production (TFYP, 2001). After Brazil and the US, China has recently become the third largest ethanol producer and consumer, with the ethanol production rising to 6.32 million tons in 2007 (YCADI, 2008). According to the national Long- and Medium-term Plan on Renewable Energy, ethanol consumption will be expected to reach 10 million tons per year by 2020.

Questions that the corn-ethanol production process might use more energy than it delivered were first raised by Chambers et al. (1979). Since then, there have been remarkable improvements in the energy efficiency of converting biomass into ethanol (Bothast and Schicher, 2005), and arguments on the net-energy value of the bio-ethanol have been reported in many countries (e.g., Berthiaume et al., 2001; Dai et al., 2005; de Carvalho Macedo, 1998; Dong et al., 2008; Elsayed et al., 2003; Graboski, 2002; Henke et al., 2005; Hu et al., 2004; Leng et al., 2008; Murphy et al., 2011; Nguyen et al., 2007a, 2007b, 2008; Nguyen and Gheewala, 2008. Ou et al., 2009; Patzek, 2004; Pimentel, 1991, 2003; Pimentel and Patzek, 2005; Reijnders and Huijbregts, 2007; Shapouri et al., 1998, 2002; Sheehan et al., 2004; Wang et al., 1997; Yang et al., 2009; Zhang et al., 2009). These studies provide very different results, with net energy values ranging from highly positive to negative. In 2007, Von Blottnitz and Curran (2007) reviewed 47 published assessments that compared bio-ethanol systems to conventional fuel ones with various system scales and boundaries. Recently, Bureau et al. (2010) suggest that the large variability across studies can be explained by the degree to which particular inputs (e.g., nitrogen, farm labor) are accounted for and by the way fossil energy consumption is allocated to the various co-products.

In China, several earlier researchers have claimed that more energy was produced in corn-ethanol processes than consumed as the processes became more and more efficient with improvement in technology (Dai et al., 2005; Huang et al., 2001; Zhang, 2005; Zhang et al., 2009). These studies, as listed in Table 1 with energy input and energy output data, ranging in quality of detail and accuracy, have been performed in different ways without covering the waste treatment process. With different system scales and boundaries, it is interesting to find that more positive energy was gained in 2001 than in 2009, in terms of energy output to energy input in these studies. Ou et al. (2009) used the

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0301-4215/$ - see front matter
doi:10.1016/j.enpol.2011.10.055

Table 1
Previous energetic accountings on corn-ethanol in China (MJ/kg ethanol).

Authors	Huang et al.	Dai et al.	Zhang	Zhang et al.	Ou et al.	Yang et al.
Year of publication	2001	2005	2005	2009	2009	2009
Energy input (MJ/kg)	45.92	24.64	29.03	32.26		164.68
Agricultural process	11.48	11.97	8.63			32.91
Industrial process	34.44	12.35	17.23			26.39
Transport	3.17	0.50	3.17			2.17
Waste treatment						103.21
Energy output (MJ/kg)	68.00	26.48	34.98	35.64		29.52
Heat of ethanol	27.20	26.48	29.66	26.50		29.52
Co-products energy	40.80		5.32	9.14		
Energy output/input	**1.48**	**1.07**	**1.20**	**1.10**	**0.89**	**0.18**

Tsinghua-CA3EM (China Automotive Energy, Environment and Economy Model) model, which was based on China's national conditions with the integration of the widely known transportation energy micro-level computing GREET model (Wang, 2007), and presented energy consumption of China's current six biofuel pathways. The results indicated that the fossil energy inputs were about 1.13 times the energy contained in corn-ethanol. Yang et al. (2009) used the cumulative exergetic method based on the integrated process including agricultural crop production, corn transportation, industrial conversion and waste treatment as a whole to identify the renewability of total corn-ethanol production in the national level of China. They concluded that 3.84 times more energy was consumed in corn-ethanol processes than was produced. However some of the pivotal energy intensity coefficients were adopted from sources for other countries in Yang et al.'s study. Furthermore, nonrenewable energy input was not identified from total energy input. A synthesis of methods, facts and data related to the production of the corn ethanol in China has not been thoroughly pursued, and a substantial accounting of nonrenewable energy cost revealing the present situation in China should be systematically made to achieve a concrete assessment.

In the present study, nonrenewable energy cost instead of overall energy cost is calculated and compared with the amount of energy delivered to society through the sum of nonrenewable energy (NE) embodied in all resources entering the supply chain of corn-ethanol processes in China, including agricultural crop production, industrial conversion, and wastewater treatment. An indicator of nonrenewable energy investment in energy delivered (NEIED) is devised to reveal the extent of NE cost of corn-ethanol over that of the energy produced. In addition, the NE consumption associated with water supply and transportation of corn is estimated and the issue of co-product credits is briefly discussed. Policy implications regarding China's energy conservation, energy security and food security are also presented.

2. Methodology

Net energy analysis of an energy technology is a comparison of energy output with the energy needed to supply all inputs – the energy source, materials, and services – to construct, operate and dispose of the technology (Herendeen, 2004). Most remarkable in the net energy analysis originally proposed at the time of the first energy crisis in the 1970s is the basic concept of energy return on investment (EROI), defined as the ratio of the energy extracted or delivered by a process to the energy used directly and indirectly in that process (Cleveland, 2007). The reciprocal of EROI has been recently addressed by Chen and Chen (2010) as an energy cost indicator to denote how many energy times of cost used in the whole manufacturing process over the energy contained in the final product. While energy efficiency indicated by EROI remains interesting, it does not suffice to evaluate nonrenewable energy's contribution to the fabrication of corn-ethanol. For nonrenewable energy use associated with its believed dominant role in climate change, an appropriate evaluation should be addressed on how much nonrenewable energy instead of inclusive energy is consumed to produce a so-called renewable energy. Malça and Freire (2006) defined the ratio between the biofuel energy content and the fossil energy input as fossil energy ratio (FER) to identify whether a fuel is renewable. To directly denote the ratio of NE consumed in the process to the energy obtained, it is appropriate to use the reciprocal of FER termed as nonrenewable energy investment in energy delivered (NEIED) expressed as

$$\mathrm{NEIED} = \mathrm{NE}/E_b \tag{1}$$

where NE is the nonrenewable energy used directly and indirectly in the production process and E_b is the energy content of the bio-ethanol product. NE can be calculated as

$$\mathrm{NE} = \sum \mathrm{NE}_i = \sum (\mathrm{Input}_i \times C_i) \tag{2}$$

where NE_i denotes the nonrenewable energy used directly and indirectly in the production of the ith input, Input_i, to the whole chain of corn-ethanol production process. And to stand for the unit primary nonrenewable energy demand directly and indirectly in the production or preparation of the ith input, C_i is defined as the nonrenewable energy-intensity coefficient of the ith input. Such coefficients are estimated through process analysis in this work, based on a review of available literature and government reports in China.

NEIED is proposed to identify the nonrenewability of believed renewable energies. Significant cases could be identified for different ranges of NEIED values. $\mathrm{NEIED} < 1$ is for a renewable process in which more energy is delivered than NE invested, while $\mathrm{NEIED} > 1$ is for a nonrenewable process in which more NE is consumed than energy delivered. In addition, NEIED has already been used to identify the nonrenewability in terms of nonrenewable energy cost of other energy technologies, such as bio-diesel and solar energy in China (Chen and Chen, 2010; Chen et al., 2011).

Fig. 1 illustrates the major NE inputs to corn-ethanol production processes within the defined limited system boundary. The overall nonrenewable energy performance of corn-ethanol is determined by accounting all direct and indirect nonrenewable energy flows into the inputs in corn-ethanol processes, at the very least including agricultural crop production, industrial conversion, and wastewater treatment. Corn is produced from the agricultural process through energy-intensive farming using fertilizer, pesticides, electricity, and fossil fuels. In the industrial conversion of corn into ethanol, the dried corn is crushed and fermented, using coal and electricity. Afterwards, the ethanol solution obtained is filtered and purified through distillation.

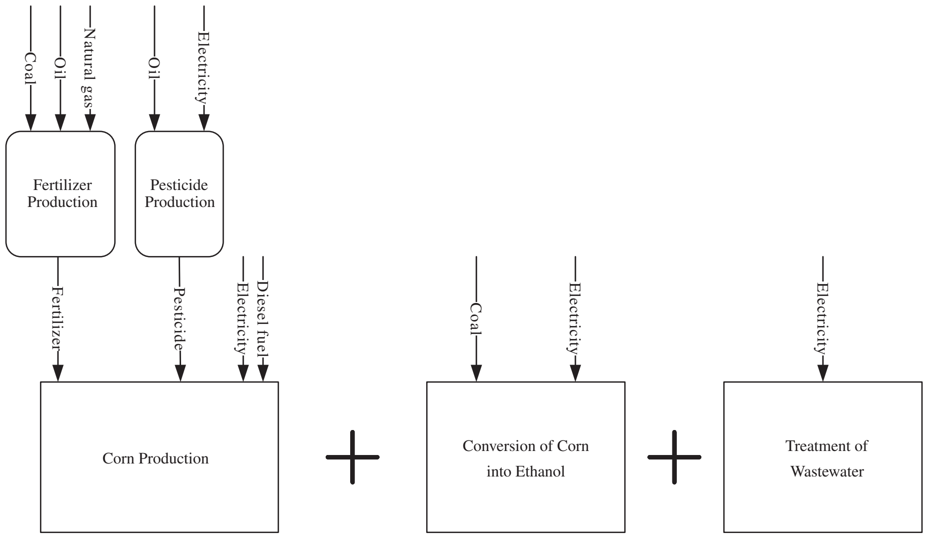

Fig. 1. Aggregated energy diagram for corn-ethanol production system.

Finally, waste or polluted substances related in the whole process, such as wastewater with organic matter, which is piped from an industrial conversion process, is treated or recovered in special facilities, mainly using electricity. All these nonrenewable inputs to corn-ethanol production processes are originally produced through the exploitation of nonrenewable energy resources. Tracing back to the primary nonrenewable energy consumption, the nonrenewable energy-intensity coefficients for main fossil energy are estimated by investigating the exploitation process based on the data published in authoritative literature in China. Thus the whole corn-ethanol process, including extraction, transport and storage of raw materials and the fabrication of intermediates is taken into account. One year is chosen as the time span for this study.

Because of different local conditions and diverse levels of technology, both inputs and their energy-intensity coefficients vary from case to case. For an average assessment at the national level, the national statistics data are reviewed and adopted. Due to deficiencies of related statistics, some NE inputs (e.g., the NE consumption associated with irrigation, agricultural pollutant treatment) are not included in the present conservative accounting. Based on a review of the agricultural-industrial corn-ethanol conditions prevailing in China, a large amount of data, such as nonrenewable energy-intensity coefficients related to main fossil energy, are calculated mostly based on the data published in the yearbooks of China (e.g., CESY, 2003–2006; CIY, 2006; CSY, 2005, 2007). The data associated with main inputs, such as those related to fertilizers during corn plantation, coal and oil consumption in industrial conversion, are obtained from both government reports and yearbooks (e.g., MWR, 2006; YCADI, 2003, 2005). Some data are from journals (e.g., Gao, 1994; Yang, 2004) and books (e.g., Gao and Guo, 2006; Liu and Liu, 1983) published in Chinese. All of these data are reviewed and verified, based on a comprehensive knowledge of energy utilization in China.

3. Estimation and results

3.1. Nonrenewable energy-intensity coefficients for fossil fuels

Nonrenewable energy cost in the production process of main fossil energy in China is estimated as follows. The lower heating values (LHVs) of coal, crude oil, and natural gas in China are 26.34 MJ/kg, 41.82 MJ/kg, and 35.15 MJ/m^3, respectively (CESY, 2003–2006). Nonrenewable energy-intensity coefficients of coal, oil products, and natural gas are estimated as shown in Tables 2–4.

Table 2
Calculation of nonrenewable energy-intensity coefficient of coal in China.

Item	Unit (MJ/kg)
Coal mining	1.95 (Ma, 2002)
Coal washing	0.42 (CIY, 2006)
Coal transportation	0.81[a]
Nonrenewable energy-intensity coefficient of coal	29.52

[a] 10.80% of the transportation was by highway with an average distance of 59.20 km; 73.80% was by railway with a average distance of 563.00 km; 15.40% was by waterway with an average distance of 1911.10 km (CTC, 1997). The diesel consumption intensity by highway was 0.05 l/(t km), and the density of diesel is 0.83 kg/l; the diesel consumption intensity by railway was 0.025 kg/(t km); the diesel consumption intensity by waterway was 0.06 kg/(t km) (CSY, 2005).

Table 3
Calculation of nonrenewable energy-intensity coefficient of diesel in China.

Items	Unit (percentage or MJ/kg)
Crude oil loss ratio in the oil field	2.00% (CESY, 2003–2006)
Direct energy consumption in the manufacture	3.11 (Gao, 1994)
Crude oil loss ratio in the machining	1.08% (CESY, 2003–2006)
Nonrenewable energy-intensity coefficient of diesel	46.18

Table 4
Calculation of nonrenewable energy-intensity coefficient of natural gas in China.[a]

Items	Unit (MJ/m^3)
Coal consumption	9.13
Oil consumption	0.29
Nonrenewable energy-intensity coefficient of natural gas	44.56

[a] The total natural gas production was 34.13 billion m^3 in 2003 (CCIY (2005–2006)), consuming 10.55 billion kg coal and 0.21 billion kg oil (CIY, 2006).

3.2. Nonrenewable energy-intensity coefficients for electricity

Nonrenewable energy-intensity coefficients of electricity are calculated in terms of thermal power and hydropower in the unit of MJ/MJ as follows.

The national average coal consumption in thermal power plant is 356.00 g/kWh (CESY, 2003–2006). The service power consumption rate is 7.10%, and the average energy line loss rate is 7.52% (CESY, 2003–2006). These data give a national average nonrenewable energy-intensity coefficient of thermal power of 2.64 MJ/MJ in 2002.

Ma (2002) estimated, respectively, the average steel and cement consumption of 1672.20 kg/kW and 10,042.00 kg/kW by hydropower plants based on a survey of main hydropower plants in China. The national average NE costs of cement and steel are 5.34 MJ/kg and 23.06 MJ/kg, respectively (CESY, 2003–2006). Additionally, the service power consumption rate is 0.49%, and the average line loss rate is 7.52%. It is assumed that the average life-span of a hydropower plant is 50 years (Berthiaume et al., 2001). The load rate of hydropower is 38.00% (CESY, 2003–2006). Then the national average nonrenewable energy-intensity coefficient of hydropower is 0.17 MJ/MJ based on all these data.

With 15.00% of electricity generated from hydroelectric sources and 85.00% from fossil fuel in China (CESY, 2003–2006), the average nonrenewable energy-intensity coefficient of electricity is calculated to be 2.27 MJ/MJ.

3.3. NE cost of the agricultural process

Statistics showed that China consumed 30.00% of the total chemical fertilizers of the world in 1997, with nitrogen, phosphate and potassium fertilizers used up to 174.00, 31.00 and 21.00 kg per hectare, respectively (Sheldrick et al., 2003). According to the research of optimum prescription on fertilizer location experiment in the main corn production area of China (Dai et al., 2005), the optimum balanced fertilizer proportion is 2.5:1:1, in terms of 187.50 kg of N, 75.00 kg of P_2O_5, and 75.00 kg of K_2O for one hectare of corn. Amongst all the published data for corn cropping fertilization, the minimum data are the national averages for these major field chemicals reported by Ministry of Agriculture of China, as 165.00 kg of N, 60.00 kg of P_2O_5, 31.50 kg of K_2O per hectare of corn farmland (Yang, 2004), which are adopted in this study for a conservative accounting.

Pesticides include insecticide, herbicide, and fungicide. In 2004, the export of pesticide from China took up 19.50% of global total pesticide exportation, and China ranked the leading importer of pesticide in the world (CSY, 2005). Meanwhile, the national production of pesticide increased rapidly and took the first place in the world with an annual yield of 1.30 million tons in 2006 (CSY, 2007). Hua and Dan (1999) estimated that the average insecticide used in a hectare of farm land would be 4.50 kg in 2000. Conservatively, 4.00 kg of insecticide is estimated applied in a hectare of farm land. According to the proportion of 4:4:1 in terms of insecticide, herbicide, and fungicide consumption in China (CSY, 2005), 4.00 kg herbicide and 1.00 kg fungicide are estimated to be consumed in a hectare of farm land.

Electricity and diesel oil are also consumed by machines in the fields. According to the Agro-Technical Economic Manual (Liu and Liu, 1983), 972.00 MJ of electricity and 15.00 kg of diesel were consumed by machinery per hectare annually. Due to lack of nationwide data, the NE consumption of water for irrigation and associated equipment is ignored in this study.

3.3.1. NE inputs to potash fertilizer production

In terms of resource restriction and market conditions, China's potash production capacity is not sufficient and 85–90% of domestic consumption is imported (Gao and Guo, 2006). Thus the nonrenewable energy-intensity coefficient of potash of 13.78 MJ/kg reported by Food and Agriculture Organization (FAO, 1999) is adopted in this paper.

3.3.2. NE inputs to phosphorous fertilizer production

In recent years, phosphorous fertilizer industry has developed rapidly, with a total production of 7.39 million ton in 2001, which ranked the second in the world (Yang, 2004). The self-sufficiency rate of China-made phosphorous fertilizer was 96.40% in 2005 (Wu, 2006). In this regard, high-concentration phosphate fertilizer industry was fully capable of competing with imports in market, based on a high growth of product output and a big drop in product cost (Wu, 2006). However, the import of high-concentration phosphatic compound fertilizer remained high, contributing to 70–85% of domestic apparent consumption (Gao and Guo, 2006). Thus the nonrenewable energy-intensity coefficient of high-concentration phosphate fertilizer provided by FAO is employed as 17.44 MJ/kg (FAO, 1999) in this paper. On the other hand, from 2000 to 2004, the proportion of low-concentration phosphorous fertilizer in the total output of phosphorous fertilizer dropped from 64.60% to 46.00% (Wang et al., 2006). The energy consumption was 200–500 kg of coal (Xu, 1982) in yielding 1 t of low-concentration phosphorous fertilizer for the condition prevailing in China 1982. Considering the technological development, it is estimated that producing 1 kg of low-concentration phosphorous fertilizer would consume 0.20 kg of coal in China recently. The nonrenewable energy-intensity coefficient of coal is 29.52 MJ/kg as calculated in Table 2. Thus the mean nonrenewable energy-intensity coefficient of phosphorous fertilizer is calculated as 12.13 MJ/kg.

3.3.3. NE inputs to nitrogenous fertilizer production

After years of technological advancement and upgrading, China is now the world's largest producer of nitrogenous fertilizer and urea. Nitrogenous fertilizer mainly refers to urea and ammonium bicarbonate in China. Based on reports by Feng (2005), the NE consumption in nitrogenous fertilizer production is estimated.

(1) NE inputs to urea production

Urea can be produced from coal, natural gas, and heavy oil. Coal-based urea is derived from ammonia. Production of 1 kg of ammonia consumed 1.11 kg of coal and 5.12 MJ of electricity (Feng, 2005). The production of 1 kg of coal-based ammonia in a midsize plant on average consumed 0.59 kg of ammonia, 1.49 kg of coal, and 0.69 MJ of electricity in China (Feng, 2005). With respect to the nonrenewable energy-intensity coefficients of coal and electricity calculated above, all of these data yield a mean nonrenewable energy-intensity coefficient of coal-based urea as 71.74 MJ/kg.

To produce 1 kg of natural gas-based urea consumed about 1 m^3 of natural gas whatever the size of the plant (Feng, 2005). A large-sized plant consumed 0.22 MJ of electricity when producing 1 kg of urea. However, middle-sized and small-sized plants consumed about 3.24 MJ of electricity to produce 1 kg of urea on average (Feng, 2005). In practice, 40.00% of gas-based urea is produced in large-sized plants, and the rest in middle-sized and small-sized plants. As a result, the nonrenewable energy-intensity coefficient of natural gas-based urea could be calculated as 49.17 MJ/kg.

Oil-based urea shares a low proportion in China's urea industry. On average, 1 kg of oil-based urea consumed 0.80 kg of heavy oil and 2.16 MJ of electricity (Feng, 2005). The production process of heavy oil is allied with diesel, thus the energy-intensity coefficient of diesel is employed as the one of heavy oil. Finally, the nonrenewable energy-intensity coefficient of oil-based urea is estimated as 41.85 MJ/kg.

In practice, 62.00% of urea was produced from coal, 26.00% from natural gas, and 12.00% from heavy oil (Feng, 2005). With these proportions, the nonrenewable energy-intensity coefficient of urea is calculated as 62.28 MJ/kg.

(2) NE inputs to ammonium bicarbonate production
Most of the ammonium bicarbonate plants are coal based and small-sized. On average, to produce 1 kg of ammonium bicarbonate was to consume 0.50 kg coal and 1.44 MJ of electricity (Feng, 2005). Thus the nonrenewable energy-intensity coefficient of ammonium bicarbonate is calculated as 18.03 MJ/kg.
(3) NE inputs to nitrogenous fertilizer production
In 2004, the production of urea was 43.73 million tons with a nitrogen percentage of 46%, while the production of ammonium bicarbonate was 49.31 million tons with a nitrogen percentage of 17% (XHPMDB, 2005). This means that 20.12 million tons of nitrogen was derived from urea and 8.38 million tons from ammonium bicarbonate in 2004. Then the proportion of nitrogen from urea to the total nitrogen fertilizer was 71.00%, and that from ammonium bicarbonate was 29.00% (Feng, 2005). Considering the energy-intensity coefficients of urea and ammonium bicarbonate are 74.29 MJ/kg and 23.34 MJ/kg, respectively, the nonrenewable energy input to 1 kg nitrogenous fertilizer is estimated to be 126.89 MJ/kg.

3.3.4. NE inputs to pesticide production

The production process of pesticide was energy-intensive, and the energy-intensity was considered remarkably greater in China than in the developed countries (Wang, 1999). For a conservative account considering the shortage of domestic data availability, we adopt the nonrenewable energy-intensity coefficients for pesticides in Turkey, as 101.20 MJ/kg for insecticide, 216.00 MJ/kg for fungicide, and 238.00 MJ/kg for herbicide (Erdal et al., 2007).

3.4. NE cost in the conversion of corn into ethanol

According to the Yearbook of China Alcoholic Drinks Industry 2003 (YCADI, 2003), the average consumption of coal for producing a ton of ethanol was about 700.00 kg and that of electricity was 200.00 kWh. With a yield ratio of 0.32, the corn production of 4925 kg/ha in 2002 (CAY, 2003) corresponds to an ethanol yield of 1576 kg/ha. Then, 1103.20 kg of coal and 1134.72 MJ of electricity would be consumed for the production of ethanol by the corn harvested from a hectare of land area.

3.5. NE cost associated with wastewater treatment in ethanol plant

YCADI (2003) documented that 40 million m^3 of wastewater resulted when 2.10 million t ethanol were produced in 2002. Approximately, for 1 kg of ethanol, 18.80 l of wastewater with an average BOD concentration of 55.00 g/l (Jia and Ying, 2005) needs to be treated. Based on a survey of energy consumption in municipal wastewater treatment facilities in China, the average electricity consumption was 1.30 kWh per kg BOD removal in the wastewater treatment process (Wang et al., 1992). Overall, these data yield an average value of electricity consumption for wastewater treatment of 1.34 kWh (or 4.84 MJ) per kg of ethanol. Thus, 7627.84 MJ of electricity is consumed when 1567 kg of ethanol is produced.

3.6. Evaluation of NEIED

As for corn-ethanol processes, NE inputs are listed and summarized in Table 5.

In corn-ethanol processes, ethanol is the final product, with energy content provided by Szargut et al. (1988). On average, 1576 kg of ethanol is produced from the corn harvested in a hectare of land area in China. The specific energy content E_b of the bio-ethanol product is thus obtained as 46,516 MJ/ha. Then, NEIED is evaluated as 1.70.

Table 5
Nonrenewable energy cost in the corn-ethanol production process.

Process	Quantity	Unit	Energy-intensity coefficients (MJ/unit)	Total NE cost (MJ)
Agricultural process				
Diesel fuel	15.00	kg	46.18	692.70
Phosphorus (P_2O_5)	60.00	kg	12.13	727.80
Nitrogen (N)	165.00	kg	126.89	20,936.85
Potassium (K_2O)	31.50	kg	13.78	434.07
Herbicide	4.00	kg	238.00	952.00
Fungicide	1.00	kg	216.00	216.00
Insecticide	4.00	kg	101.20	404.80
Electricity	972.00	MJ	2.27	2206.44
Total in agricultural process				26,570.66
Industrial conversion				
Coal	1103.20	kg	29.52	32,566.46
Electricity	1134.72	MJ	2.27	2575.81
Total in industrial conversion				35,142.27
Wastewater treatment				
Electricity associated with BOD removal	7627.84	MJ	2.27	17,315.20
Total in waste treatment				17,315.20
Total				79,028.13

The NEIED value reveals that ethanol production using corn grain required another 0.70 times more energy derived from fossil fuels than the energy delivered from the ethanol produced, implying that the production of the corn-ethanol is with a high nonrenewability for the condition prevailing in China.

For the NE cost, as presented in Fig. 2, 44.47%, 33.62%, and 21.91% are due to industrial conversion, agriculture, and wastewater treatment, respectively. NE cost in the agricultural process, in terms of the usage of fertilizers, mainly ammonium nitrate, takes up 26.49% of the total NE cost.

The percentages of NE cost in terms of the usage of phosphorous fertilizer, potash fertilizer, pesticide, and diesel fuel are no more than 1.00%. Then the estimation uncertainties associated with these inputs are not significant for the overall assessment.

4. Validation

Due to limited data availability, many other NE inputs, side effects and co-products have not been reflected in the above accounting.

4.1. Other NE inputs

Water consumption associated with corn-ethanol processes is large in view of irrigation water and ethanol plant feed water. Patzek (2004) estimated for the case in the U.S. that 10 million liters of water was required for one hectare of crop, and 0.81 million liters came from pumping groundwater and surface water to irrigate corn. For ethanol plant, YCADI (2003) published the datum of an average of 0.05 million liters of water consumed in producing 1000 kg of ethanol. This translates into 0.08 million liters for 1576 kg ethanol per hectare of corn. Thus 0.89 million liters of water is estimated to be consumed in corn-ethanol processes based on one hectare of farmland. All these data indicate that about 706 l of water is directly consumed in producing 1 l of ethanol, even in the case that the indirect water consumption is not taken into account. This issue is highly significant in China, where the freshwater resource per capita was only one-fourth of the world's average (MWR, 2006). Furthermore, electricity, which is generated with a high nonrenewable

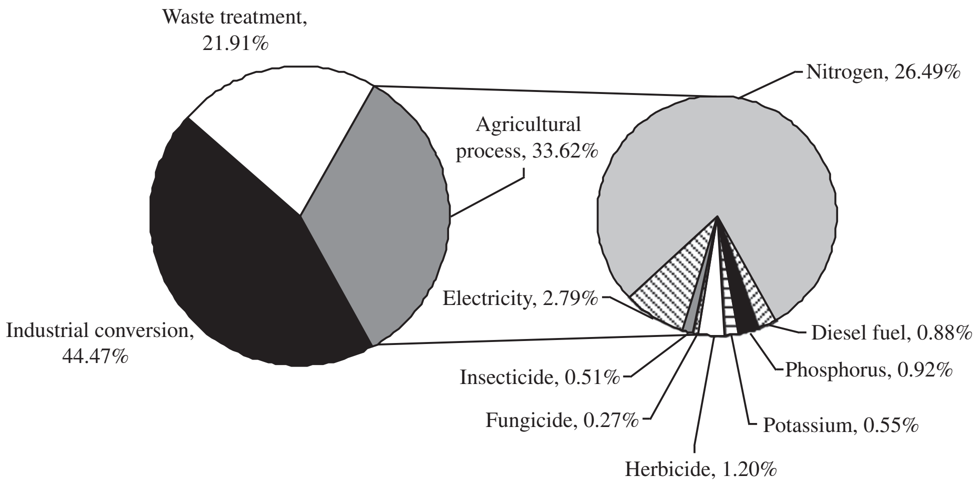

Fig. 2. NE cost fractions for corn-ethanol production processes.

NE consumption, is consumed in water supply facilities. In China, 0.39 kWh of electricity (Chen, 2003) was used to supply one cubic meter of tap water. If half of the 0.89 million liters of water is supplied by tap water, this will consume 623.00 MJ of electricity, corresponding to 1413.90 MJ of NE per hectare, accounting for 3.04% of E_b. With the NE cost of water consumption included, the NEIED would increase to 1.73.

NE cost in transportation was referred to chemicals for farming transported into the fields, corn transported into the ethanol plant, and personal commute (Patzek, 2004). As a test, let us only consider the NE consumption of corn transportation to the ethanol plant. First, it is assumed that corn is transported on the highway by diesel vehicles, with the average transport distance of 300 km (Zhang, 2005). The consumption intensity of the diesel is estimated as 0.05 l/(t km). The nonrenewable energy-intensity coefficient of diesel is 46.18 MJ/kg, and diesel density is 0.83 kg/l. The NE value of the transport of corn is thereby calculated to be 2831.58 MJ/ha, taking up 6.09% of E_b. Thus the NEIED would increase to 1.76.

Agricultural non-point source pollution contributes most to the eutrophication in aquatic systems. If agricultural polluted water was treated, 37,940.00 MJ/ha of electricity would be consumed (Yang et al., 2009), leading to a striking value of 3.55 for the NEIED.

Overall, the calculated value of NEIED (1.70) would rise to NEIED′ (3.64) when covering part of the NE cost associated with water consumption, transportation and environmental remediation.

4.2. Co-product credits

Wet mill ethanol plants produce many co-products including carbon dioxide, corn gluten feed, corn gluten meal, and corn oil, while dry mill ethanol plants produce ethanol, carbon dioxide, and dried distillers grains. Major disagreements surface when different researchers come to credit the energy flows associated with various co-products to offset the high NE cost of ethanol production. Multiple allocation approaches were evaluated including: (1) allocation approaches based on mass, energy, and market value, (2) system expansion approaches with co-product crediting (also known as the "displacement method" or the "substitution method"), (3) process-purpose-based approach (Shapouri and McAloon, 2004), and (4) consequential approach assessing the incremental impact of stover production and refining (Kaufman et al., 2010). Wang et al. (2011) calculated the energy credit assigned to co-products of corn-ethanol as 14%, 44%, 37%, 22%, and 34%, based on displacement, mass, energy content, market value, and process purpose, respectively. Table 6 shows how results change with different allocation methods for co-products. Even with the maximum energy credit mentioned, the NEIED′ value remains notably greater than unity when covering part of the NE cost associated with water consumption, transportation, and environmental remediation. Patzek (2004) gave ethanol zero energy credit, as the high environmental restoration costs in ethanol production from corn required the ethanol refineries to bear the transportation and disposal costs for gluten feed, meal, and all other solid and liquid wastes from ethanol production, and suggested that all of the ethanol processing leftovers should be returned to the field to replenish soil humus and micro-elements. In this study, Patzek's method is adopted.

Table 6
Results change with different allocation method.

	Ethanol (%)	Co-products (%)	NEIED	NEIED′
Without allocation method	100	0	1.7	3.64
With allocation method				
Displacement	86	14	1.46	3.13
Mass	56	44	0.95	2.04
Energy content	63	37	1.07	2.29
Market value	78	22	1.33	2.84
Process purpose	66	34	1.12	2.40

5. Discussion and concluding remarks

For corn-ethanol in China, the nonrenewability indicator of NEIED, defined as nonrenewable energy investment in energy delivered, is estimated as 1.70, manifesting a high nonrenewability of the production of corn-based ethanol instead of the believed renewability. For a conservative estimation with some inputs not included, the corn-ethanol production requires 0.70 times more nonrenewable energy (NE) than the energy content of ethanol produced. The calculated value of NEIED would rise to 3.64 when the other NE costs associated with water consumption, transportation, and environmental remediation are covered. Remarkably, the goal of NE conservation could not be achieved by corn-ethanol production with the technology conditions prevailing in China.

Due to the coal dominated nonrenewable energy structure in China, corn-ethanol processes in China are mostly a conversion of coal to ethanol and that is, solid fuel to liquid fuel. As corn-ethanol consumption in China is expected to rise to 10.00 million tons compare to oil demand of 500.00 million tons in 2020 (EFYP, 2006) and with the estimation of 6.50 million tons gasoline to be substituted by the ethanol according to the heat value, 1.30% of the oil demand can be met by ethanol in China 2020. Thus, as substitution of conventional gasoline, corn-ethanol is used not to supplement the fossil fuel supply, but to convert the embodied coal equivalent into the gasoline equivalent to realize the goal of oil saving and further, to adjust the consumption structure of fossil fuels.

In addition, NE cost is just one aspect of biofuels production. More questions concerning water crises and cultivated land use have emerged, with the most serious problem of competition for land between corn-ethanol and food. Food security is an inevitable concern for China with limited land resources compared with a huge population. Huang (2006) reported that 48.00% of national total ethanol yield is derived from corn in China 2004. As total ethanol yield was 2.29 million tons in 2004 (YCADI, 2005), 3.43 million tons of corn was estimated to be converted into ethanol based on a conversion ratio of 0.32. As the total corn yield was 25.65 million tons in China 2004 (CAY, 2005), this means that 13.38% of corn was used in the ethanol purpose. The corn output increased from 107.00 million tons in 2000 to 140.00 million tons in 2005, with an annual increase of 5.90% in grain yield (CENN, 2006). Meanwhile, corn deep-processing plants consumed more than 23.00 million tons of corn in 2005 compared to 12.50 million tons in 2001 (CENN, 2006). Obviously, the growth rate of corn deep-processing industrial expansion went far beyond the annual increase in corn yield. Thus, the corn price kept rising even though the annual corn yield increased in China.

China's biofuel policy initially supported corn-ethanol plant in the background of "digesting" the stale grain in the 1990s. To promote the application of biofuel in China, PetroChina and SinoPec have blended fuel with gasoline, and distributed and sold E10 as fuel for road transport in nine provinces of China (YCADI, 2005). Large amounts of subsidies and incentives have also been allotted for biofuel projects. During the National Tenth Five-Year Plan period (2001–2005), fuel ethanol producers enjoyed favorable policies, including free income tax, Value-Added Tax (VAT) refunding, fiscal subsidies (TFYP, 2001). In 2005, the Chinese government provided more than 2 billion Yuan in subsidies for fuel ethanol producers to offset the price difference between gasoline and fuel ethanol. To reduce the expenses on the financial price subsidies and encourage the ethanol producer to reduce costs, Chinese government also adjusted the subsidy policy from flex price subsidy to fixed price subsidy as 1373 Yuan per ton ethanol in 2006 (NDRC, 2006). Concerned over globally rising grain prices, in June 2007, the Chinese Central Government banned the use of grain crops to produce ethanol during the Eleventh Five Year Plan period (2006–2010), and urged the biofuel industry to change the production input from food as feedstock to non-food related materials, such as sorghum, cassava, sweet potato, cellulose, etc. (NDRC, 2007). In September 2007, NDRC issued notices on corn based ethanol, setting out that corn deep-processing should be under strict control, and no new corn-based ethanol plant would be approved (NDRC, 2007). In the Eleventh Five-Year Plan, the government also claimed investor and operator of biofuel plant should be selected through bidding, and should meet the criteria for stable feedstock supply, high energy sufficiency, and effective environmental protection (EFYP, 2006). In the 2008 International Proseminar of China State Biomass Energy, the Ministry of Agriculture of China asserted that China would develop biofuel industry step by step with "Chinese Characteristics", and insisted on developing biofuels without competing with grain for land (Wei, 2008). These policies have substantially dampened the momentum of corn-ethanol development in China. It is clear that the central government ruled out the feasibility for China to use staple food grains for fuel because of the paramount priority of food security.

In general, it is suggested that corn based ethanol is not a proper alternative renewable energy source in long term fossil energy saving planning due to its intensive NE consumption and potential conflicts against food security in China.

Acknowledgments

This study has been supported by the National Natural Science Foundation of China (No. 10972009). We would like to thank Dr. Bin Chen and Dr. John Coulter for their valuable comments.

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